Measurements of the Turbulent Fluxes of Momentum, Moisture and Sensible Heat over the Ocean

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ABSTRACT

This paper describes results of measurements of the fluxes of momentum, moisture and sensible heat by both the eddy correlation and "dissipation" techniques. The data were collected on the *R/V Flip* during BOMEX (Barbados Oceanographic and Meteorological Experiment) and during a pre-BOMEX trial cruise near San Diego in February 1969. The results are mainly based on data collected by personnel from Oregon State University and the University of British Columbia. We are grateful to the University of Washington personnel who have made their data and results available to us to check some of our results and allowed us to use their temperature fluctuation data from the San Diego cruise when our equipment failed to provide such data.

The methods of determining the fluxes are discussed. The instrumentation and methods of data analysis are described. The effects of *Flip*'s interference on the flow are described and the method of removing the interference from the results is given. The spectra of the three components of velocity fluctuations and the cospectra between the vertical velocity fluctuations w and the downstream velocity u, temperature T, and humidity q fluctuations are presented. The fluxes determined by the eddy correlation method are compared with fluxes estimated from the rates of dissipation of kinetic energy and scalar fluctuations. These fluxes are then used to evaluate the constants in the bulk aerodynamic formulas for estimating the fluxes.

The normalized velocity component spectra and the normalized uw cospectra appear to have universal forms and are similar to earlier results. The normalized wT cospectra do not appear to have a universal form. The normalized wq cospectra do appear to have a universal form and are very similar to the normalized uw cospectra. As has been found before, the dissipation and eddy correlation methods agree quite well on the average for the momentum flux. The two methods do not give the same results for the sensible heat flux for BOMEX although there is fair agreement for the small number of San Diego results. The two methods do give good agreement for the moisture flux. Comparison of the eddy correlation flux for momentum with the mean wind speed squared leads to a drag coefficient of 1.5×10^{-3}. The sensible heat flux, however, does not show a good relationship with the mean wind speed times the mean sea-air temperature difference during BOMEX. For the San Diego results the relationship is fair and similar to other measurements. The moisture flux shows a strong correlation with the wind speed times the mean sea-air humidity difference. The non-dimensional aerodynamic evaporation coefficient (corresponding to the drag coefficient for momentum) was found to be 1.2×10^{-3} with an uncertainty of about 20%. This result based on direct measurements of the flux agrees rather well with some earlier indirect estimates based on evaporation pan data.

1. Introduction

This paper describes results of measurements of the fluxes of momentum, moisture and sensible heat obtained by both the eddy correlation and "dissipation" techniques. The data were all collected from the *R/V Flip* (floating instrument platform) which is operated by the Marine Physical Laboratory of Scripps Institution of Oceanography (Bronson and Glosten, 1968). The results are based mainly on data collected during the BOMEX experiment in May 1969 but include a few measurements from a pre-BOMEX trial cruise made off San Diego in February 1969.

The measurement program was a cooperative one with investigators from the University of California at San Diego, University of Washington (UW), University of British Columbia (UBC) and Oregon State University (OSU). The OSU-UBC measurements were strongly integrated since the UBC personnel measured velocity fluctuations and the OSU personnel temperature and humidity fluctuations. The results in this paper are based largely on the OSU-UBC measurements. We are grateful for the cooperation of the other groups on

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board for supplying supplementary and comparative data. As part of the program the UW personnel made observations of wet and dry bulb temperatures with an Assmann psychrometer and of sea surface temperature. We have used these values and our flux measurements to obtain aerodynamic formulas for estimating the fluxes. In addition, we are extremely grateful to UW for permission to use their data in the following ways. First, for the use of their cup anemometer results to check (and in the case of the BOMEX data, to correct) the mean velocities obtained from the sonic anemometer. Second, for the use of their temperature fluctuation data from the San Diego cruise during which time the OSU-UBC equipment did not provide such data. The use of these temperature data allowed us to compute the sensible heat flux during this cruise for comparison with our other results.

The analysis of these data has been complicated by the effects of *Flip* on the velocity measurements. While *Flip* is very stable compared to a surface ship, she does rock back and forth in the waves and spurious contributions to the velocity spectra are introduced at wave frequencies. *Flip* also rotates back and forth around her vertical axis and introduces spurious contributions to the spectrum of the cross-stream (v) velocity component mainly at frequencies <0.01 Hz. The most serious effect is that *Flip* apparently tilts the whole flow field by 5–10° in the vertical so that the mean wind has a downward component. The first and second effects can be fairly well removed from the final flux values. Correction for the vertical tilt can be made but is complicated by the second effect and is based on a fairly strong assumption. Even if this assumption is correct, considerable uncertainty in the final flux values is introduced (15–25% in the momentum flux and 5–10% in the moisture and sensible heat fluxes).

Although the instruments were mounted some 14 m from the side of *Flip*, the distance was not sufficient to remove the strong tilt effect. We expected some effect because *Flip*'s cross section through the sea surface is smaller ($\sim$3.5 m) than her cross section higher up at the observation level (approximately 8 m), but were surprised that the tilt was so large. Part of this tilt in the vertical may also have been produced by the flow interference of the main horizontal boom (an open box section about 30 cm high) which was about 2 m above the instruments. Because of mounting arrangements, the sonic anemometer was probably only level within 2 or 3°, so this apparent tilt in the flow was verified by observing, with the horizon for reference, a streamer (1-mil magnetic tape) attached to the sonic array.

Since even a tilt of 2–3° cannot be neglected when computing the fluxes (Pond, 1968), the lack of a correction for a tilt of 5–10° would make the final results meaningless. We felt that we could remove small instrument tilts in the way proposed by Smith (1967), by rotating the coordinate system until the correlation between the vertical (w) and downstream (u) components of velocity had the right behavior as a function of frequency. While such an approach requires that the correlations as a function of frequency for the present measurements be the same as for those of Smith (1967) and Weiler and Burling (1967), the assumption seems to be quite reasonable. The same approach can be used for correcting for the tilt in the flow plus the instrumental tilt. In this case, however, we must make the much stronger assumption that the *Flip* induced tilt in the flow does not distort the Reynolds stress (uw) in such a way that the correlation between u and w is affected. We have made this assumption because we could not obtain results by the eddy correlation technique in any other way. The final results for velocity are consistent with other measurements and give us some faith in the correctness of our assumption and in the results for the scalar (moisture and sensible heat) fluxes. The procedure for rotating the coordinates is given in more detail in Section 3e.

The dissipation technique of estimating the fluxes was also used. Fortunately, it is not very sensitive to tilt. Since the dissipation technique has been compared with the eddy flux method for momentum before, we can use this method to check that our rotations have given reasonable results for the momentum, and hence the other eddy fluxes. This method has never, to our knowledge, been tried for the scalar fluxes. Our results, therefore, provide a preliminary test of this method for these scalar fluxes.

Finally from our flux values and observations of wind speed and sea-air temperature and humidity differences, we have evaluated the coefficients in the aerodynamical formulas for estimating the fluxes. These coefficients should be of interest to the other investigators in BOMEX for comparison with their results. Because of analysis difficulties the momentum (drag) coefficient must be regarded primarily as a check on our analysis. During BOMEX the latent heat flux provides 85–90% of the total heat flux. The coefficient for moisture (and hence latent heat) flux should, therefore, be the most useful result of our aerodynamic analysis.

2. Methods of determining the fluxes

a. Eddy correlation method

This method is based on obtaining averages of the vertical velocity with the parameter of interest; thus, we have

$$\left.\begin{aligned}&\text{Momentum flux}=-\rho\overline{uw}=\tau\\&\text{Sensible heat flux}=\rho C_p\overline{wT}=H_s\\&\text{Moisture flux}=\overline{wq}=E\\&\text{Latent heat flux}=L\overline{wq}=H_L\end{aligned}\right\},\qquad(1)$$

where the overbar indicates averaging, ρ is the air density (for San Diego $\rho=1.24\times10^{-3}$ gm cm^{-3}, for BOMEX $\rho=1.16\times10^{-3}$), u the velocity fluctuation in the downstream direction, w the vertical velocity fluctuation, C_p the specific heat at constant pressure [1.00×10^7 ergs gm^{-1} (°C)$^{-1}$], T the absolute temperature (°K), q the absolute humidity (μg cm^{-3}), and L the latent heat of vaporization (for San Diego $L=2460\times10^7$ ergs gm^{-1}, for BOMEX $L=2440\times10^7$ ergs gm^{-1}).

The choice of units for the final flux values is not standardized for the heat fluxes. We have chosen to use milliwatts (mW) per square centimeter (1 mW cm^{-2} $=10^4$ ergs cm^{-2} sec^{-1}) because they give convenient numbers. Some conversion factors are: 1 mW cm^{-2} $=14.3$ mcal cm^{-2} min$^{-1}=20.6$ cal cm^{-2} day^{-1}. We express the moisture flux in μg cm^{-2} sec^{-1}, where 1 μg cm^{-2} sec^{-1} is equivalent to an evaporation rate of 0.86 mm of water day^{-1} or 31.6 cm of water year^{-1}. The stress or momentum flux is given in dynes per square centimeter.

In practice, we determine the fluxes by integrating the cospectrum Φ_{wx} (x may be either u, T or q), which has the property that

$$\overline{wx}=\int_0^\infty \Phi_{wx}(f)df. \qquad (2)$$

We cannot of course integrate over all frequencies. The lower limit is set by the record length and the upper limit by the response of the instrument. By examining the measured cospectra we can determine whether or not we have included all frequencies which make significant contributions to the flux. We can also remove any wave-induced *Flip* motion effects by correcting the cospectrum in the wave-frequency band. Likewise, variances are obtained by integrating the corresponding spectrum Φ_x, which has the property that $\overline{x^2}=\int_0^\infty \Phi_x(f)df$, where x may represent any fluctuating quantity.

b. Dissipation method

This method has been compared with the direct (eddy correlation) method by various investigators concerned with the evaluation of the momentum flux (e.g., Smith, 1967; Weiler and Burling, 1967; Miyake *et al.*, 1970a). It is based on the assumption that the production of mechanical energy is equal to the dissipation of mechanical energy at the same height in near neutral conditions, i.e.,

$$\text{production}=-\overline{uw}\frac{dU}{dz}=\text{dissipation}=\epsilon, \qquad (3)$$

where u, w are defined as before, U is the mean wind speed and z height. Assuming the logarithmic profile, we have

$$\frac{dU}{dz}=\frac{u_*}{\kappa z}, \quad u_*^2=-\overline{uw}, \qquad (4)$$

where κ is von Kármán's constant (0.4). Therefore,

$$u_*^2=(\kappa\epsilon z)^{\frac{2}{3}}. \qquad (5)$$

The value of ϵ can be determined from the inertial subrange of the downstream velocity spectrum, i.e.,

$$\Phi_u(k)=K'\epsilon^{2/3}k^{-5/3}, \qquad (6)$$

where K' is the one-dimensional Kolmogoroff constant and k the radian wavenumber obtained from the frequency using Taylor's hypothesis, $k=2\pi f/U$ (Pond *et al.*, 1966). The dissipation ϵ may also be determined from the second-order structure function in the inertial subrange (the method actually used), i.e.,

$$D_{uu}(r)=\overline{[u(x+r)-u(x)]^2}=4.02K'\epsilon^{\frac{2}{3}}r^{\frac{2}{3}}, \qquad (7)$$

where x is the coordinate in the downstream direction, $r=-Ut$ is the separation between the points of observation, and t is time.

The results obtained by the investigators mentioned above give stresses from the dissipation which are higher than the eddy correlation stresses. This discrepancy can be explained, at least partially, in terms of some new results that have become available. The value obtained for u_*^2 depends inversely on K', the Kolmogoroff constant, and the value 0.48 was used. However, on re-examining the data used to obtain K' in Grant *et al.* (1962), Nasmyth (1970) found some corrections were necessary leading to a revised value of 0.56. From an examination of the second- and third-order structure functions for u (from the same data set as that used in this paper) Paquin and Pond (1971) obtained a K' of about 0.55. Using $K'=0.55$ reduces the value obtained for $\epsilon^{\frac{2}{3}}$, and hence u_*^2, by some 15%. Busch and Panofsky (1968) and Wyngaard and Coté (1971) have shown in recent investigations of the turbulent energy budget that dissipation is approximately equal to mechanical production plus buoyant production B. Thus, in Eq. (5), $\epsilon-B$ might be more appropriate than ϵ. Only the paper of Miyake *et al.* (1970a) provides sufficient information to make both corrections. The average buoyancy correction is only about 5% for their data. With both corrections, their drag coefficient C_D from dissipation is reduced to 1.1×10^{-3}, in good agreement with both eddy flux ($C_D=1.09\times10^{-3}$) and profile measurements (C_D $=1.13\times10^{-3}$).

In our computations of $(u_*^2)_\epsilon$ we obtain ϵ from Eq. (7) using $K'=0.55$ and correct for the buoyant production in Eq. (5) with

$$B=g\left(\frac{\overline{wT}}{\bar{T}}+\frac{\bar{T}}{273}\times0.47\times10^{-3}\,\overline{wq}\right), \qquad (8)$$

where g is the acceleration of gravity (980 cm sec^{-2}) and $\bar{T}$ the absolute temperature (for San Diego 284K, for BOMEX 300K). Note that we have included the effect of the humidity fluctuations in the buoyant production.

There is one further effect which we have not included. It is well known that in unstable conditions the gradients (profiles) of wind speed and temperature or humidity are less than those obtained from formulas based on near neutral conditions (Lumley and Panofsky, 1964), although there is some disagreement on the best method of correcting for this reduction. We include a discussion of the scalars, denoted by γ, since we need the results later. We use γ to represent either humidity, potential temperature $\{T+\Gamma z$, where Γ is the adiabatic lapse rate$\}$, or the potential virtual temperature[2] $\{\Theta=T[1+0.47\times10^{-3}(T/273)q]+\Gamma z\}$. We adopt the profile forms for unstable conditions used by Miyake *et al.* (1970a) since they lead to successful comparisons between profile and eddy correlation methods of obtaining the momentum and sensible heat fluxes; thus, we have

$$\left.\begin{aligned}\frac{dU}{dz}&=\frac{u_*}{\kappa z}\alpha^{-1}\\ \frac{d\bar{\gamma}}{dz}&=\frac{\gamma_*}{z}\alpha^{-2}\end{aligned}\right\}. \tag{9}$$

The correction factor $\alpha=(1-16\,\mathrm{Ri})^{\frac{1}{4}}$, where the Richardson number $\mathrm{Ri}=(g/\bar{\theta})(d\bar{\theta}/dz)/(dU/dz)^2$, and $\gamma_*=-\overline{w\gamma}/(\kappa u_*)$. With this definition of Ri and profiles of the type shown in (9), we have

$$\mathrm{Ri}=\frac{z}{L}=-g\left(\frac{\overline{wT}}{\bar{T}}+\frac{\bar{T}}{273}\times0.47\times10^{-3}\,\overline{wq}\right)\Big/(u_*^3/\kappa z),$$

where the right-hand side is the negative ratio of the total buoyant and mechanical productions, neglecting stability effects on dU/dz, and L is the Monin-Obukhov length with both humidity and temperature effects included. We note that the effect on the scalar profiles is larger than that on the wind speed profile. With this stability effect included, we have

$$(u_*^2)_\epsilon=[\kappa(\epsilon-B)z]^{\frac{2}{3}}\alpha^{\frac{2}{3}}. \tag{10}$$

We have not included the $\alpha^{\frac{2}{3}}$ in our calculation of $(u_*^2)_\epsilon$ since neglecting it gives better results both for our data and those of Miyake *et al.* (1970a). The average C_D by the dissipation method would be increased about 15% for their results and 25% for ours. Eq. (3) neglects any vertical diffusion of turbulence energy. As instability increases and dU/dz decreases, the production rate lower down becomes relatively greater which may increase the upward flux. Such an increased flux might compensate for the reduced local production, at least for the moderate range of stability of our results, making a correction to $dU/dz=u_*/(\kappa z)$ unnecessary.

An analogous method can be used to obtain values for the scalar fluxes from the dissipation, N_γ, of the scalar fluctuations. We again equate production with dissipation (of $\overline{\gamma^2}/2$, proportional to potential energy), giving

$$-\overline{w\gamma}\frac{d\bar{\gamma}}{dz}=N_\gamma, \tag{11}$$

where N_γ, is obtained from the spectrum or, equivalently, from the structure function $D_{\gamma\gamma}$, the method actually used. Thus, in the inertial-convective subrange, we have

$$\left.\begin{aligned}\Phi_\gamma&=B_\gamma' N_\gamma\epsilon^{-1/3}k^{-5/3}\\ D_{\gamma\gamma}&=\overline{[\gamma(x+r)-\gamma(x)]^2}=4.02B_\gamma' N_\gamma\epsilon^{-\frac{1}{3}}r^{\frac{2}{3}}\end{aligned}\right\}, \tag{12}$$

where

$$\int_0^\infty \Phi_\gamma(k)dk=\overline{\gamma^2},\quad N_\gamma=3\eta_\gamma\int_0^\infty k^2\Phi_\gamma dk,$$

η_γ is the kinematic diffusivity, and B_γ' is the Kolmogoroff constant for scalar fluctuations. We now obtain the dissipation ϵ from Eq. (7) for use in Eq. (12). Substituting in (11) from (9) we have $\kappa u_*\gamma_*^2\alpha^{-2}z^{-1}=N_\gamma$, which, with the use of $[\kappa(\epsilon-B)z]^{\frac{1}{3}}$ for u_*, becomes

$$\kappa u_*\gamma_*=\alpha(\kappa z)^{2/3}N_\gamma^{1/2}(\epsilon-B)^{1/6}. \tag{13}$$

Note that in this formulation we have included the gradient correction factor for the scalar gradient but not for the velocity gradient. Including the second correction would have changed the factor in (13) from α to $\alpha^{7/6}$, a difference of about 5%. We include the α factor in the scalar gradient because the method empirically gives better results when it is included. Wyngaard and Coté (1971) have found that the flux divergence term in the temperature fluctuation energy budget is always small compared to local production and hence production approximately equals dissipation. Thus, the flux divergence cannot compensate for the reduced local production caused by the decrease in $d\bar{\gamma}/dz$ with increasing instability.

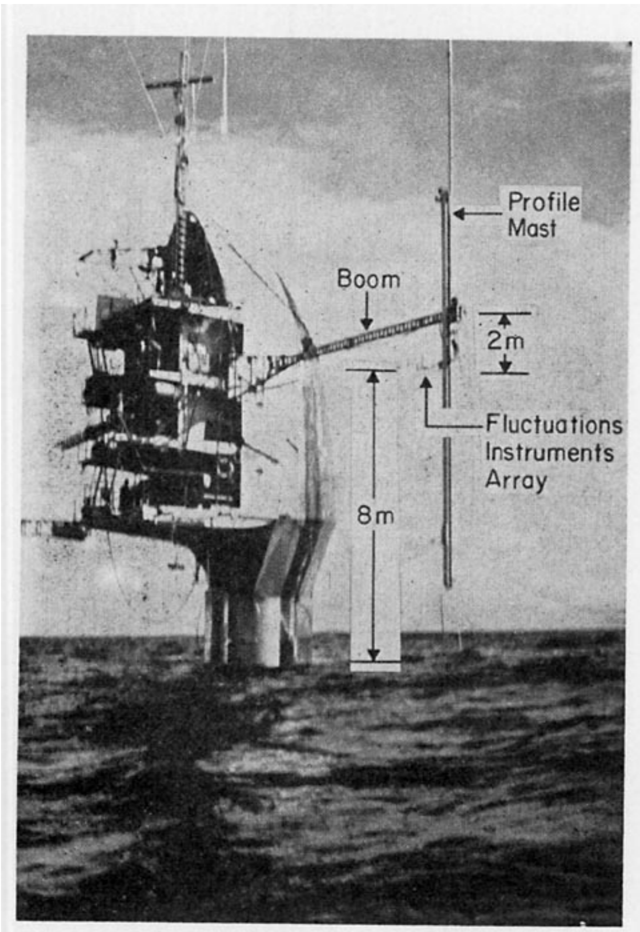
Because we are testing this method, we obtain B from the measured eddy correlations. If one only had estimates of the dissipation rates one would initially use ϵ in (13) to obtain an estimate of B, and then iterate until B converged. Since $(\epsilon-B)$ occurs as a 1/6 power and $B<\epsilon$ under usual conditions over the ocean, convergence would be rapid. For example, $\epsilon^{1/6}$ and $(\epsilon-B)^{1/6}$ for our data differ by less than 6%.

The reason this method has not really been tested before is that the value of B_γ' has not been well established. There are a number of recent measurements of this constant, but there is still some disagreement.

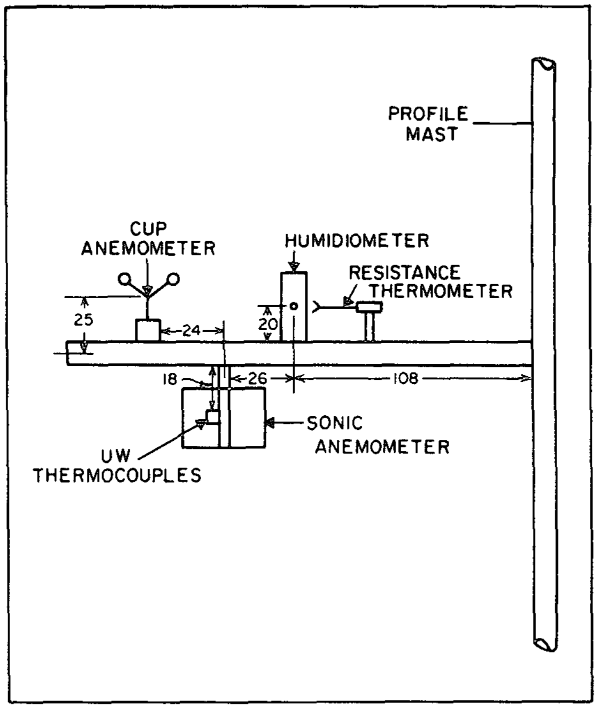
[2] The virtual temperature takes this form rather than the more familiar form $T(1+0.61q')$, where q' is specific humidity (gm gm^{-1}), because of the units chosen for q (μg cm^{-3}) which are otherwise convenient. The factor $0.47\times10^{-3}(T/273)=0.61/\rho$, where ρ is air density (gm m^{-3}). Likewise, this same q factor appears in the expressions for B and Ri.

Wyngaard and Coté (1971) obtain N_T by measuring all the other terms in the energy balance equation for $T^2/2$ and obtain 0.79±0.10 (mean ± standard deviation) for B_T'. By examining second- and third-order structure functions for both temperature and humidity, Paquin and Pond (1971) obtain a B_γ' of 0.82±0.12 with no difference between temperature and humidity within the variance of the results. Gurvich and Zubkovsky (1966) give values of 0.9 from structure functions and quote an earlier result of 0.7, for comparison. We have used the value $B_\gamma'=0.8$ in our calculations since it is based on measurements in the region of the spectrum which we are using to obtain N_T and N_q for estimating the fluxes. Paquin and Pond (1971) discuss some other measurements, some in agreement with and others different from the value 0.8, so further discussion is omitted here.

The dissipation method is somewhat empirical and has uncertainities because of the assumptions made and uncertainty about the exact values of the Kolmogoroff constants. However, it is very attractive because it is simpler than the eddy correlation and profile methods and can be used under conditions of flow distortion and platform motion which would make these other methods difficult if not impossible.



a.



b.

Fig. 1. Photograph of *R/V Flip* with instrumentation array, a., and schematic diagram, b.

c. Aerodynamic methods

From a practical point of view it is more useful if one can relate these fluxes to more standard observations such as mean wind speed and sea-air temperature and humidity differences, i.e.,

$$\left.\begin{aligned} \tau/\rho &= -\overline{uw} = C_D U^2 \\ H_s/(\rho C_p) &= \overline{wT} = C_T U \Delta T \\ H_L/L = E &= \overline{wq} = C_q U \Delta q \end{aligned}\right\}, \tag{14}$$

where ΔT is the difference between sea surface temperature and the air temperature at a reference height and Δq the corresponding mean moisture difference. Roll (1965) discusses the derivation of these equations and suggests that $C_D \approx C_T \approx C_q$ for conditions not too far from neutral.

3. Data collection and instrumentation

Fig. 1 shows the arrangement. The instruments were about 14 m from *Flip* and about 8 m from the water (for San Diego 8.5 m; and for BOMEX 8.1 m for OSU runs 5–11 and UBC runs 1–5, and 8.6 m for OSU runs 12–15). The vertical boom could be brought in about two-thirds of the way where the instruments were accessible from a catwalk. The arrangement was not ideal; we would have preferred to have the instruments outboard of the profile mast or further below the horizontal boom but did not have time to modify the mechanical arrangements to make a better mounting possible. The vertical tilt of the flow is probably associated with the mounting arrangement as well as the presence of *Flip* itself.

It was planned that *Flip* would be oriented with the main deck facing the wind and the boom perpendicular to the wind. It was not possible to maintain this orientation exactly but the data have been selected from cases when the angle was within 30° of the desired direction and usually with the boom slightly upwind of *Flip* rather than downwind. During the San Diego experiment *Flip* was attached to an anchor by a bridle and maintained her heading fairly well although there was some rotation about the vertical axis. During BOMEX it was not possible to anchor *Flip*. Instead the tug which towed *Flip* out was attached to a bridle with about 800 m of line. This arrangement, with *Flip* a sort of "sea anchor" for the tug, worked reasonably well some of the time, particularly after the tug began to steam slowly (10 rpm) downwind instead of just drifting. By selecting data it was possible to find runs for which this rotation did not affect the analysis too badly, about comparable to the San Diego data.

a. Velocity measurements

The three components of velocity were measured with a Kaijo Denki model PAT-311 ultrasonic anemometer. This instrument is widely used now and has been described before (e.g., Miyake *et al.*, 1970b). It measures both fluctuations and the mean velocity. The mean velocity is obtained by using the observed average of the fluctuations output and the offset values which are inserted to balance out the mean flow. These zero offsets are independent of the fluctuations part of the circuitry and its calibration. Because cup anemometers are more reliable for measuring mean speeds, we checked the sonic anemometer against the profile values measured by the University of Washington group with a Beckman and Whitley cup anemometer. The time periods are not always exactly the same, so the comparison could not be exact. We found that for the San Diego data the two values were the same within $\pm 5\%$. For the BOMEX data there was apparently a zero offset in the magnitude of the sonic anemometer velocities of 80 cm sec^{-1} for OSU runs 5–11 and UBC runs 1–5 and 125 cm sec^{-1} for OSU runs 12–15. Note that there is a break in the data collection between OSU runs 5–11, UBC runs 1–5 and OSU runs 12–15, while *Flip* was towed back into the BOMEX array. Some adjustments were made to the sonic anemometer during this break (apparently not for the better) and these adjustments explain the difference in offsets between the two sets of data.

With this offset correction the two instruments again agreed within $\pm 5\%$ (with the exception of OSU run 8 where the angle of attack was rather poor). We have used the corrected sonic anemometer velocities and feel that they are accurate to about 5%. Fortunately, the fluctuations calibration is independent of the zero offset and is also accurate to 5% or perhaps a bit better.

b. Temperature measurements

With the kind permission of the UW Department of Atmospheric Sciences we used their temperature fluctuations data for OSU runs 1–4 (San Diego) when the UBC temperature equipment did not work and the OSU temperature equipment was not on board. The sensor is a very small thermocouple with a high gain dc amplifier attached. Calibration is accurate to within 5% and the response is 3 db down at about 3 Hz which is sufficient to measure the flux.

During BOMEX, temperature fluctuations were measured with the OSU platinum resistance thermometer with calibration accuracy of 3–5% and 3 db point at 80 Hz (Phelps *et al.*, 1970).

c. Humidity measurements

The humidity fluctuations were measured with the OSU α-Lyman humidiometer which is manufactured by Electromagnetic Research Corp. The instrument has just begun to be used in the atmospheric boundary layer. Phelps *et al.* (1970) describe the mechanical additions made at OSU and also some early results. Miyake and McBean (1970) show a comparison between this instrument and a dew point hygrometer and discuss flux measurements made with this instrument over land. Now that we have used this instrument more extensively, additional comments on its operation are in order. The output voltage of the instrument has the form

$$V = V_0 \exp(-\lambda q), \tag{15}$$

where λ is a constant which depends on path length, the absorption coefficient for water vapor, and on the current through the α-Lyman source tube. Since the path length is kept fixed during calibration and subsequent experiments, we can ignore this dependency. The constant λ is then determined by calibration against a psychrometer or some other standard device for a range of source tube currents I (0.08–1 mA in the instrument used) and humidity values. Above 0.25 mA or so λ changes very little with source tube current but is rather more sensitive at low values of I. This variation is presumably due to changes in the output spectrum of the source tube as the current through the tube is changed. The sensitivity probably varies from tube to tube. As the tube is used, it ages and its output goes down so the instrument is not reliable for measuring the mean humidity over periods longer than a day or so. Fortunately, it appears that the fluctuations calibration is pretty well independent of the source tube aging, at least at fairly large source tube currents where λ is independent of this current. To demonstrate this feature we rewrite Eq. (15). We define $\bar{q}$ by $\bar{V}=V_0\exp(-\lambda\bar{q})$, where $\bar{V}$ is the average voltage over a data run. Then putting $q=\bar{q}+q'$ in (15), we have

$$\left.\begin{aligned} V&=V_0\exp(-\lambda\bar{q})\exp(-\lambda q')=\bar{V}\exp(-\lambda q') \\ &\text{or} \\ q'&=-\frac{1}{\lambda}\ln\frac{V}{\bar{V}} \end{aligned}\right\}. \tag{16}$$

Note that while $\overline{q'}\neq 0$, $\overline{q'}\ll\bar{q}$ or $\bar{q}$. As the source tube ages, V and $\bar{V}$ go down in proportion, but $\ln(V/\bar{V})$ varies in the same way. If λ does not change as the tube ages, the fluctuations calibration is independent of the source tube aging. Based on our experience during the BOMEX experiment, it seems that λ did not change as the tube aged. Because the fluctuations are fairly small, (16) can be linearized with an accuracy of 1 or 2% for our data runs to give

$$q'\approx-\frac{V'}{\lambda\bar{V}},\quad V'=V-\bar{V}. \tag{17}$$

The OSU analysis is based on (16) while the UBC analysis is based on (17).

It is rather difficult to give a good value for the 3-db point of this instrument since there is no better responding instrument to compare it with. However, the 3-db frequency should be about 10 Hz, perhaps more for the wind speeds encountered (see Phelps *et al.*, 1970) so the flux measurements should be satisfactory.

For the San Diego data the instrument was calibrated in the laboratory and the source tube aging was small; thus, the calibration is quite reliable with an accuracy of 5–10%. The instrument was compared with the UW fluctuations psychrometer which uses small wet and dry thermocouples. The two instruments gave highly coherent signals with essentially zero phase difference below about 0.1 Hz. The psychrometer gave amplitudes from 5–10% lower than the humidiometer. A joint note on the details of this comparison and the suitability of the two instruments for flux measurements will be put out by the OSU–UW groups.

For the BOMEX operation the calibration was made onboard ship using a Bendix psychrometer (Psychron model 566) and was not as accurate. Calibrations were made before the cruise and in the break while *Flip* was being towed back into the array. Source tube aging occurred but λ did not appear to change or to differ for the two source tube currents used, generally 0.75 and occasionally 1.0 mA. We feel that the calibration is good to about ±10%.

The signals from these instruments were recorded on an analog magnetic tape recorder (Ampex FR-1300) and later digitized at UBC and analyzed by digital techniques.

d. Data analysis

We have not analyzed all the data that we collected, about 20 hr day^{-1} for 10 days during BOMEX. We feel, however, that we have analyzed a representative sample. Although much more of this data could be analyzed, it would probably not affect the overall results. Some of the data were analyzed at OSU and some at UBC. The UBC data were chosen around the time of an aircraft fly-by by other UBC personnel, while the OSU data were chosen to give data spread over the whole data collection period. Analog filtering was done before A/D conversion to eliminate electronic noise at frequencies above the band of interest. Corrections for this filtering have been made where they are significant. Both groups based their analysis on the fast Fourier transform method but there are slight differences.

For the OSU analysis, sampling was done at about 10 samples sec^{-1}. The runs were broken down into blocks of 8192 samples and the fast Fourier transform applied, giving spectra and cospectra over a frequency range of about 0.001–5 Hz, a range sufficient to obtain all significant contributions to the fluxes. Spectra and cospectra were obtained by band averaging so that the final estimates were approximately equally spaced with $\log f$ as the variable. About seven points per decade were obtained. The individual block averages were then averaged together in each frequency band to obtain the final spectra and cospectra for the run (2–7 blocks).

For the UBC analysis sampling was done at about 20 samples sec^{-1}. The runs were broken down into blocks of 1024 samples, fast Fourier transformed, band-averaged to give about seven points per decade, and averaged over the run. This high-frequency analysis gives values from about 0.1–10 Hz. To get estimates for the low frequencies the average values for each block are fast Fourier transformed. In cases where the number of blocks is not a power of two, the series is completed by making the last few points equal to the average over the whole run and the final estimates are weighted accordingly. This low-frequency analysis gives values from about 0.00025–0.01 Hz. It conserves variance, that is, the integrals under the spectra and cospectra are correct but the spectral shape and phase relationships are distorted particularly near the Nyquist frequency of 0.01 Hz. In order to make our results more comparable, the UBC spectra and cospectra were only integrated down to 0.001 Hz, that is, the same low-frequency cut off was used for all data.

An examination of the velocity spectra and the *uw* cospectra show that the wave-induced *Flip* motions are introducing spurious contributions near 0.1 Hz. (These effects can be seen on the normalized plots in the results.) One to three estimates are affected. A correction is made to the integrals by drawing a smooth curve through this region on an $f\Phi$, $\log f$ plot based on both sides of the affected region. The corrections are typically 5–10% of the total integral and thus the corrected integrals are negligibly affected by the wave-induced *Flip* motions. No wave effects are noticeable in the scalar spectra or the wT, wq cospectra.

e. Coordinate rotations

The measured velocity components in the horizontal are rotated so that one is parallel to the mean horizontal velocity and the other perpendicular. In the UBC analysis the rotation is based on the average over the whole run. In the OSU analysis the rotation is done for each block (approximately 13 min long) and the differences in angle (typically within 5° of the run average) is ignored since the effects on the results are negligible. Because of the zero offset in the sonic anemometer output which might be somewhat different for the two horizontal channels, there is some question about the accuracy of this coordinate rotation. However, we expect the vw cospectra to vanish if we are in the correct horizontal coordinate system. Examination of these cospectra indicate we are typically within 5° of the coordinate system for which these cospectra are zero, outside frequency ranges where they are affected by waves and *Flip*'s rotation around her vertical axis. Even an angle error of 0.2 rad (11.4°) in the horizontal is negligible since the stress is reduced by the factor $\cos\theta$ (0.98).

If we rotate through an angle θ in the u,w plane [a negative angle being one which makes the positive x (downstream) axis point downward], then using primes to denote values in the new coordinate system, we have

$$\left.\begin{aligned} u' &= u\cos\theta + w\sin\theta \\ w' &= w\cos\theta - u\sin\theta \\ \overline{u'w'} &= \overline{uw}\cos 2\theta - \tfrac{1}{2}(\overline{u^2}-\overline{w^2})\sin 2\theta \\ \overline{u'^2} &= \overline{u^2}\cos^2\theta + \overline{w^2}\sin^2\theta + \overline{uw}\sin 2\theta \\ \overline{w'^2} &= \overline{w^2}\cos^2\theta + \overline{u^2}\sin^2\theta - \overline{uw}\sin 2\theta \\ \overline{w'\gamma} &= \overline{w\gamma}\cos\theta - \overline{u\gamma}\sin\theta \end{aligned}\right\}. \tag{18}$$

Since these mean square and flux values are formed from sums of cospectral and spectral values, the spectra and cospectra rotate in the same way, i.e.,

$$\left.\begin{aligned} \Phi_u' &= \Phi_u\cos^2\theta + \Phi_w\sin^2\theta + \Phi_{uw}\sin 2\theta \\ \Phi_w' &= \Phi_w\cos^2\theta + \Phi_u\sin^2\theta - \Phi_{uw}\sin 2\theta \\ \Phi_{uw}' &= \Phi_{uw}\cos 2\theta - \tfrac{1}{2}(\Phi_u - \Phi_w)\sin 2\theta \\ \Phi_{w\gamma}' &= \Phi_{w\gamma}\cos\theta - \Phi_{u\gamma}\sin\theta \end{aligned}\right\}. \tag{19}$$

The rate of change with angle depends on the magnitudes of the various terms. Typical values (percent per degree) for our data are: $-\overline{uw}$, 13; $\overline{u^2}<-1$; $\overline{w^2}$, 2; $\overline{wq}$, 5; $\overline{wT}$, 3. In the Appendix we give the values that are necessary to obtain flux and variance values in any desired coordinate system.

The selection of the correct rotation in the u,w plane is rather difficult. In order to get reasonably accurate flux values, particularly for momentum, we need to be within 1 or 2° of the correct system. We have based our rotations largely on making the correlation coefficient $R_{uw}=\Phi_{uw}/(\Phi_u\Phi_w)^{\frac{1}{2}}$ approximately equal to -0.5 in the band $0.01<fz/U<0.1$. The selection of -0.5 is based on the results of Smith (1967) and Weiler and Burling (1967). We realize that for any given run $\langle R_{uw}\rangle$, the average of the six or seven estimates in this band, need not be exactly -0.5 even if we are in the correct coordinates. However, we feel that this method gets us within a degree or two of the correct system. For the UBC runs this criterion can only be applied to the high-frequency analysis which limits the band at the low end to 0.02–0.03. The rotation of *Flip* around her vertical axis sometimes appears to affect the values of R_{uw} for $fz/U<0.03$, making the selection of the correct angle of rotation somewhat subjective. The motion effects usually affect not only R_{uw} but the phase between u and w, and also R_{wv}, R_{uv}, and corresponding phases, and are sometimes associated with larger Φ_u than adjacent estimates. A low value of R_{uw} is possible statistically, but it does not affect the phase or the values of R_{wv}, R_{uv} and their phases very much and is often associated with smaller than usual values of either Φ_u or Φ_w. In the Appendix we give the values of $\langle R_{uw}\rangle$ along with some notes as to why the particular values were chosen. In the band used $\langle R_{uw}\rangle$ changes by -0.04 per degree. Because of the motion some values are less than -0.5 but the rotations are within 1° of giving -0.5 except for OSU runs 4 and 7 and UBC run 4 where the motion was particularly bad as evidenced by the large values of $\sigma_v=(\overline{v^2})^{\frac{1}{2}}$. When applying this -0.5 criterion it would be better to work at lower frequencies where R_{uw} changes more rapidly. However, the data runs are not long enough for good statistics, the motion effects are more severe, and the proper value is not known since Smith's and Weiler and Burling's results are scattered below $fz/U=0.01$. At higher frequencies R_{uw} is less sensitive to rotation, and the wave effects cause errors as well. The angles used to make $\langle R_{uw}\rangle\approx-0.5$ are typically about $-10°$. Part of this 10° may be due to leveling errors of the instrument.

This uncertainty in the correctness of the coordinate system introduces some scatter in the results so that for an individual run $\overline{uw}$ may be in error 15–25% and the scalar fluxes 5–10%. When we obtain quantities by averaging over the whole data set, the effects should be reduced to perhaps 10% for quantities based on $\overline{uw}$ and 5% for quantities based on the scalar fluxes. The use of this criterion, of course, depends on the assumption that *Flip*'s rotation of the mean flow does not affect R_{uw} in the range of fz/U which was used. The fact that the results agree in many ways with previous results gives credance to the validity of this assumption.

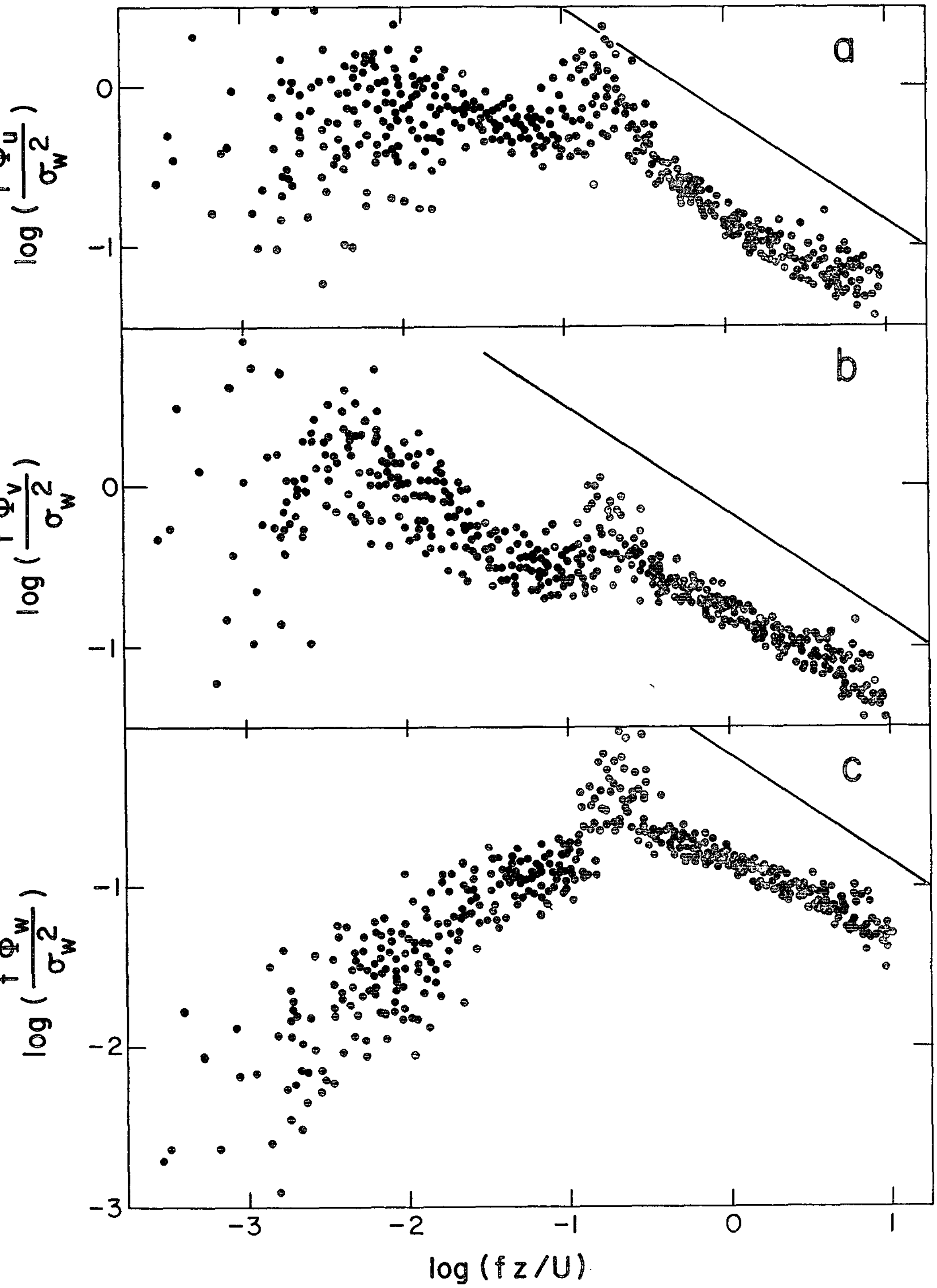


FIG. 2. Normalized u, v, w spectra vs fz/U on a log-log plot, a.–c., respectively. Straight lines have slope $-2/3$ corresponding to the Kolmogoroff $-5/3$ law.

The rotations do not have much effect on the dissipation method since the structure functions are quite insensitive to rotations of the coordinate system. A demonstration of this fact is given in Paquin and Pond (1971). There are, of course, other errors in the dissipation method because of the assumptions made and the fact that we are working near the low-frequency or large-scale limits of the inertial subrange.

4. Results

In presenting the results we have not attempted to distinguish the individual runs because there are so

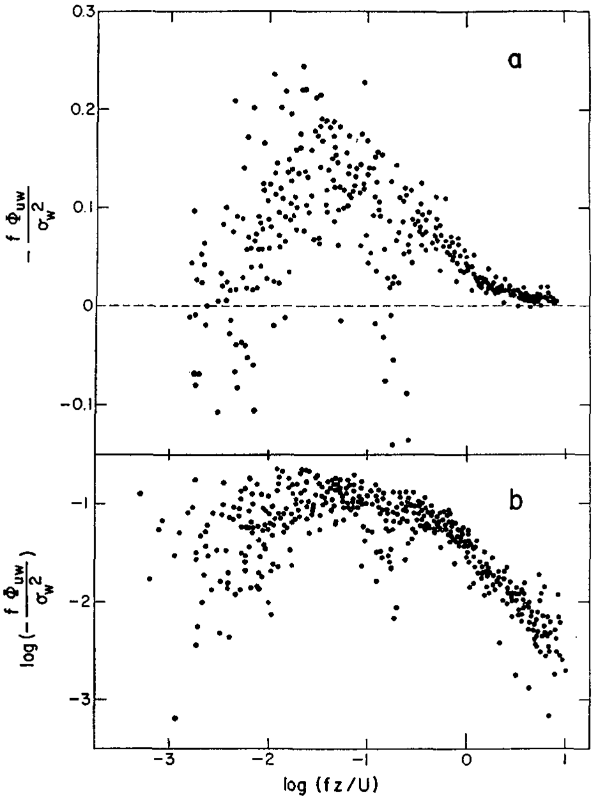


FIG. 3. Normalized uw cospectra as a function of log fz/U on a linear scale, a. (integral under curve$=u_*^2/\sigma_w^2$) and a log scale, b.

many that it would be impossible to do so on a single plot. We distinguish among different groups of data when we feel the differences are significant.

In the spectra and cospectra the lower frequency points have a narrower bandwidth and hence are subject to more statistical variation. The concept of degrees of freedom which is based on Gaussian statistics is nearly useless for atmospheric turbulence data. The observed variability from block to block within a run is larger for spectra and very much larger for cospectra than the degrees of freedom concept would predict. The actual scatter in the figures is probably as good a measure as any of the statistical variability.

a. Spectra and cospectra

Normalized spectra of u, v and w are shown in Fig. 2. The abscissa of the diagrams is the $\log_{10}$ of the "natural frequency" fz/U. The vertical coordinates are normalized with $\overline{w^2}=\sigma_w^2$. Because of the rotation problem, u_*^2, which might otherwise be used, may be more in error than usual. Because of the poorer statistics at low frequencies and the relatively greater contribution from high frequencies to σ_w^2, it is always more reliably measured than u_*^2. A comparison of these spectra with other measurements such as Miyake *et al.* (1970b) or Smith (1967) shows that the spectral shapes and levels are very similar with some differences in certain ranges. Most noticeable are the large values between $-1<\log(fz/U)<-0.5$. These peaks are due to the wave-induced *Flip* motion, and one can see that they are easy to remove as we have done in the final integrals. For $\log(fz/U)<-2$ the v spectra are on average higher than one might expect from previous results. This peaking is caused by *Flip*'s rotation about her vertical axis. The values of σ_v are correspondingly too large and no conclusions can be drawn from them. The w spectra show perhaps a bit more scatter at low frequencies due to errors in the u,w coordinate rotations. However, on the average, they are very close to the previous results. The fact that we have produced the correct shape for this spectrum lends some support to our method of coordinate rotation. There is a little bit of aliasing above $\log(fz/U)=0.5$. This aliasing is caused by setting the analog filter cutoff above the Nyquist frequency. However, it insures that no significant high-frequency contributions to the integrals were lost.

Fig. 3 shows the uw cospectra on both a linear ($f\Phi_{uw}$) and a logarithmic plot against $\log(fz/U)$. Again we have normalized with $\overline{w^2}$ rather than u_*^2. A plot normalized with u_*^2 would, in fact, look very similar except for a shift in the vertical scale since σ_w/u_* does not vary a great deal for these runs. The wave effects show up again but can and have been removed from

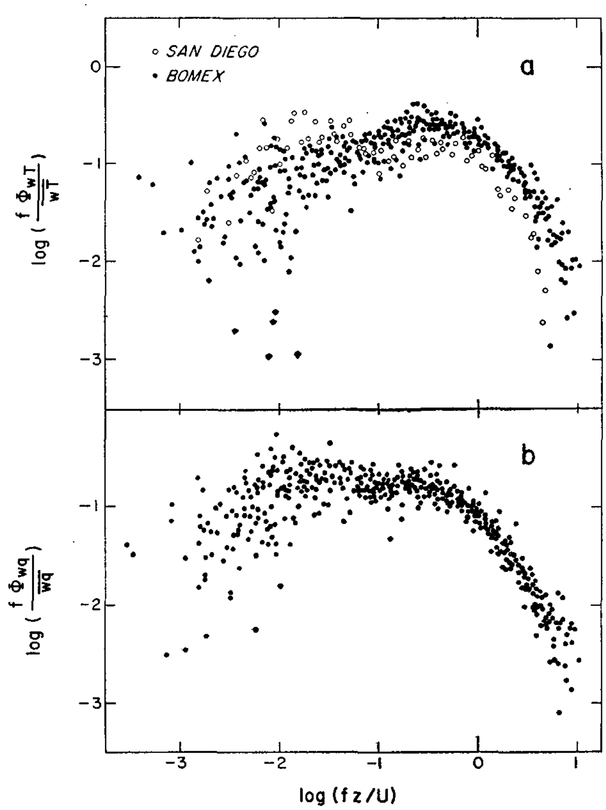


FIG. 4. Normalized wT and wq, cospectra, a. and b., respectively, on a log-log plot.

TABLE 1. Flux results.

Run	Time/date (GMT)	Duration (min)	U (m sec^{-1})	Eddy correlation $-\overline{uw}$ (cm^2 sec^{-2})	Eddy correlation σ_w/u_*	Eddy correlation 10^3C_D	Dissipation u_*^2 (cm^2 sec^{-2})	Dissipation 10^3C_D	Eddy correlation $\overline{wT}$ (°C cm sec^{-1})	Eddy correlation 10^3C_T	Dissipation κu_*T_* (°C cm sec^{-1})	Dissipation 10^3C_T	Eddy correlation $\overline{wq}$ (μg cm^{-3} cm sec^{-1})	Eddy correlation 10^3Cq	Dissipation κu_*q_* (μg cm^{-3} cm sec^{-1})	Dissipation 10^3Cq	τ (dyn cm^2)	Eddy correlation H_s (mW cm^{-2})	Eddy correlation H_L (mW cm^{-2})	Eddy correlation $R=\frac{H_s}{H_L}$	Eddy correlation $-\frac{z}{L}$
OSU																					
1	0954/20/2	40	5.78	533	1.26	1.60	354	1.06	1.59	0.99	1.50	0.93	3.22	1.21	2.50	0.94	0.66	2.0	7.9	0.25	0.20
2	1104/20/2	27	6.60	724	1.20	1.66	459	1.05	1.59	0.87	1.75	0.95	3.38	1.11	2.55	0.84	0.90	2.0	8.3	0.24	0.12
3	1517/20/2	40	4.78	378	1.33	1.66	358	1.57	0.89[a]	0.67[a]	1.73[b]	1.29[b]	1.55	0.84	1.66	0.90	0.47	1.1	3.8	0.29[a]	0.18[a]
4	0109/21/2	54	6.05	840	1.31	2.29	920	2.48	2.60[c]	1.16[c]	2.34[d]	1.04[d]	4.41	1.31	4.05	1.21	1.04	3.2	10.8	0.30	0.16
5	1909/3/5	87	4.65	356	1.33	1.65	416	1.92	0.92	3.1	2.34	8.0	5.51	1.44	6.26	1.64	0.41	1.1	13.5	0.08	0.27
6	0455/4/5	37	5.55	369	1.37	1.20	471	1.53	0.93	2.6	2.29	6.4	3.96	1.10	4.64	1.29	0.43	1.1	9.7	0.11	0.23
7	0532/4/5	25	7.22	505	1.45	0.97	502	0.96	1.18	2.5	2.38	5.1	6.25	1.33	5.00	1.07	0.59	1.4	15.3	0.09	0.20
8	0702/5/5	37	5.92[e]	618	1.41	1.76[e]	729	2.08	1.30	3.1	2.96	7.1	4.34	0.98	7.31	1.65	0.72	1.5	10.6	0.14	0.14
9	1125/5/5	37	7.21	881	1.42	1.69	801	1.54	1.51	6.3	3.34	14.0	7.45	1.33	7.46	1.33	1.02	1.8	18.2	0.10	0.11
10	0317/6/5	62	6.79	664	1.15	1.44	529	1.15	1.14	3.9	2.42	8.3	4.65	1.04	4.65	1.04	0.77	1.3	11.4	0.12	0.11
11	1816/6/5	75	5.31	383	1.26	1.36	376	1.33	0.89	4.8	2.40	12.9	4.27	1.11	4.76	1.24	0.44	1.0	10.5	0.10	0.22
12	1854/9/5	62	6.51	565	1.38	1.33	635	1.50	1.10	0.88	2.34	1.9	6.34	1.21	6.85	1.30	0.66	1.3	15.5	0.08	0.17
13	0754/11/5	62	5.86	484	1.38	1.41	562	1.63	1.12	2.6	3.03	7.0	6.51	1.29	7.16	1.41	0.56	1.3	15.9	0.08	0.22
14	1235/11/5	62	4.97	352	1.44	1.33	458	1.85	1.10	3.4	2.82	8.6	5.03	1.28	5.98	1.52	0.41	1.3	12.3	0.10	0.33
15	0311/12/5	62	6.78	686	1.29	1.49	751	1.63	1.21	2.1	3.70	6.5	7.95	1.30	8.59	1.41	0.80	1.4	19.4	0.07	0.15
UBC																					
1	1145/6/5	43	6.88	675	1.31	1.43	...	...	1.59	5.5	...	...	6.48	1.33	...	...	0.78	1.8	15.8	0.12	0.16
2	1431/6/5	45	6.10	628	1.25	1.69	...	...	1.27	6.0	...	...	6.39	1.45	...	...	0.73	1.5	15.6	0.09	0.15
3	1811/6/5	42	5.48	424	1.26	1.41	...	...	1.10	5.8	...	...	5.33	1.34	...	...	0.49	1.3	13.1	0.10	0.24
4	1902/6/5	28	5.01	381	1.14	1.51	...	...	0.78	4.5	...	...	3.69	1.02	...	...	0.44	0.9	9.0	0.10	0.20
5	1959/6/5	44	3.93	246	1.41	1.59	...	...	0.77	5.5	...	...	4.54	1.59	...	...	0.29	0.9	11.1	0.08	0.40
Average values					1.32	1.52		1.55						1.23		1.25					
Standard deviations					0.09	0.26		0.40						0.17		0.25					

[a] Values based on only 13 min of data.
[b] Values based on 27 min of data.
[c] Values based on 27 min of data.
[d] Values based on 40 min of data.
[e] Cup anemometer indicates about 10% higher speed than corrected sonic anemometer mean velocity during the early part of this run which may be due to the large angle (30–40°) between the wind and the sonic array. Using the cup anemometer speed gives $C_D=1.4\times10^{-3}$.

the final integrals. We note, too, the occasional negative values (which cannot be shown on the log plot) at low frequencies on the linear plot. Such negative values can and do occur because of statistical variations and are one of the reasons why such parameters as σ_w/u_* and C_D show quite a lot of scatter. There is quite a lot of scatter at low frequencies partly from errors in the rotation and partly from statistical variations. We have not done any smoothing (such as hamming or hanning) other than band and block averaging. Not all the large values on the plots are associated with any one run and, in general, the cospectra appear to have converged fairly well at low frequencies. As for the velocity spectra, our results for the *uw* cospectra are similar to other measurements.

The normalized *wT* and *wq* cospectra are shown in Fig. 4. The normalization of the vertical coordinate has been done with the corresponding flux values $\overline{wT}$ and $\overline{wq}$. There are a few small negative values at low frequencies in these cospectra which are omitted in these log plots. The *wq* cospectra are very similar in shape to the *uw* cospectra. From measurements over land Miyake and McBean (1970) have found the same similarity in their measurements. Our *wq* cospectra are similar to theirs. For the *wT* cospectra we have distinguished between the San Diego and BOMEX data because they seem to be different. The *wT* cospectra for the San Diego data are very similar to the *wq* cospectra. (OSU Run 3 is not included since there are only 13 min of temperature data. The last few values at high frequency are probably low due to reduced response of the temperature sensor.) For the BOMEX data much more of the contribution to $\overline{wT}$ is at high frequencies.

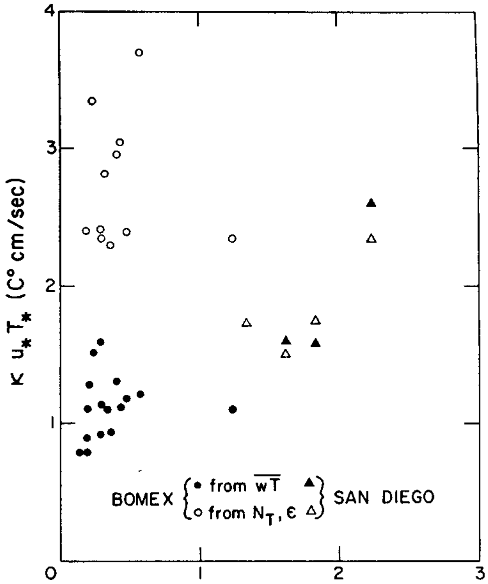


FIG. 6. $\kappa u_* T_*$ vs 10^{-3} $U\Delta T$.

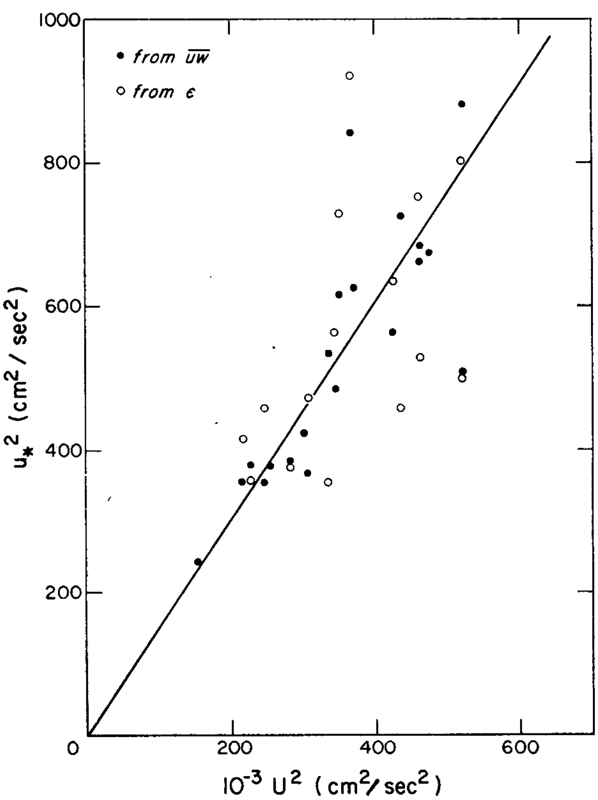


FIG. 5. u_*^2 vs 10^{-3} U^2. The straight line corresponds to $C_D = 1.52\times 10^{-3}$.

b. Fluxes

Table 1 summarizes the flux results. (Supplementary data and data related to the rotations are given in the Appendix.) Actual stress values τ, heat fluxes, the Bowen ratio R (sensible heat flux/latent heat flux), and the stability parameter z/L are given in the last columns. These values are based on the eddy correlations. Values from the dissipation methods may be calculated using the formulas and parameter values in the section on methods of determining the fluxes.

The flux values in the table are presented graphically in Figs. 5–7. Fig. 5 shows u_*^2 determined by both eddy correlation and dissipation methods as a function of U^2. Fig. 6 shows the temperature flux ($\kappa u_* T_*$) as a function of $U\Delta T$. (There is one BOMEX run which appears to fit better with the San Diego data than with the other BOMEX data. This difference arises because the recorded ΔT is rather larger than for any other BOMEX run. We suspect that there may be a reading error in T_{air} of 1C since the recorded values around this run show larger variations than were usually typical. We cannot find an obvious error and have therefore included this result although it is somewhat questionable.) Fig. 7 shows the moisture flux as a function of $U\Delta q$.

5. Discussion

a. *The ratio σ_w/u_* and r_{uw}*

The average value of σ_w/u_* for our results is 1.32 ± 0.09 ($\pm$ figures are standard deviations). This value is somewhat smaller than the results obtained by Miyake *et al.* (1970a) of 1.47 ± 0.26 (eight runs) and Miyake and McBean (1970) of 1.49 ± 0.13 (four runs). It is larger than the values summarized in Lumley and Panofsky (1964) which range from 0.7 to 1.33 with a suggested "best value" of 1.05. McBean (1970) obtains 1.53 ± 0.16 from extensive measurements over land (79 runs with z/L negative). Busch and Panofsky (1968) suggest that the value is 1.3 for unstable conditions. If the value of this ratio were better established, it might provide an alternative method of rotating in the vertical, although it is somewhat less sensitive to rotation than $\langle R_{uw}\rangle$, changing only about -6% per degree. Higher values of this ratio would lead to lower values of C_D and $-\langle R_{uw}\rangle$. The values of the overall correlation, $-r_{uw}=-\overline{uw}/\sigma_u\sigma_w[\sigma_u=(\overline{u^2})^{\frac{1}{2}}]$ would also be reduced (12% per degree). Our average value of $-r_{uw}$ is 0.262 ± 0.035 which agrees well with the values 0.250 ±0.058 obtained by Miyake *et al.* (1970b). Our values might be expected to be slightly lower because σ_u may be slightly larger than it should be because of the motion effects. The criterion that $-r_{uw}=0.25$ could have been used instead of the criterion $\langle R_{uw}\rangle=-0.5$ but it is perhaps less well established and in our case made slightly less reliable by the motion effects. However, our average value satisfies this criterion which suggests that our rotation method is valid. The values of r_{uw} are given in the Appendix and show that, in general, we are within a degree or two of satisfying the criterion $r_{uw}=-0.25$. The fact that r_{uw}, σ_w/u_* and $\langle R_{uw}\rangle$ are all reasonable, both for the individual runs and for the average, and that the shapes of the spectra and uw cospectra look right gives considerable support to the validity of our eddy correlation fluxes.

We cannot see any particular trend in σ_w/u_* as a function of stability, but our range of z/L values is small. It has been suggested that σ_w/u_* increases as $-z/L$ increases, but this increase must at best be very small—at least for moderate values of $-z/L$ (values $<\frac{1}{2}$–1). It is well known that the buoyancy production term $2B$ initially enhances $\overline{w^2}$. It is often overlooked that in the corresponding equation for the rate of change of $\overline{uw}$ there is a term like B which tends to increase $\overline{uw}$. This term is identical in form to B [Eq. (8)] except that u replaces w. The values $\overline{uT}$ and $\overline{uq}$ are also given in the Appendix, and it can be seen that the buoyancy production term in the $\overline{uw}$ equation is usually larger than $2B$. This term will at least prevent σ_w/u_* from increasing rapidly with $-z/L$. With a greater range of stability McBean (1970) shows a very slightly increasing trend for unstable conditions. The trend is not very certain because it is small compared to the scatter. Busch and Panofsky (1968) suggest that σ_w/u_* is independent of z/L for unstable conditions.

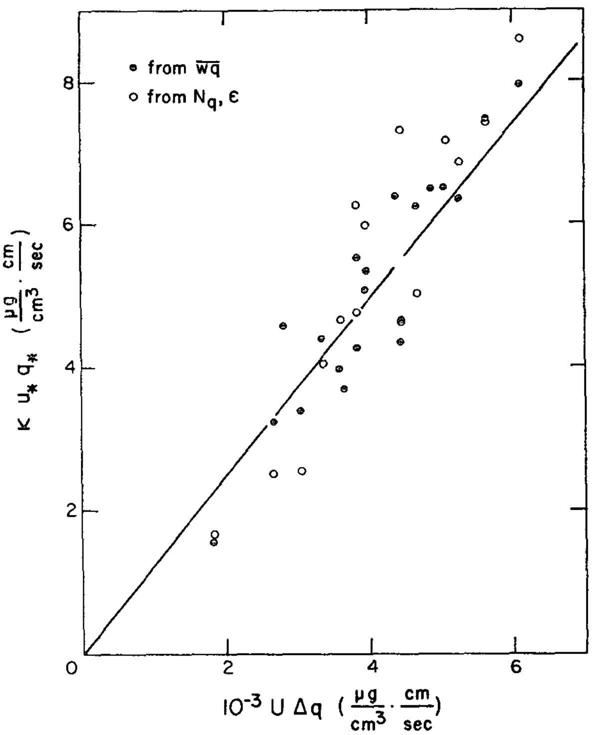


FIG. 7. $\kappa u_* q_*$ vs $10^{-3}\ U\Delta q$. The straight line corresponds to $C_q=1.23\times10^{-3}$.

b. *Normalized spectra and cospectra*

All the spectra have been normalized in a way consistent with the Monin-Obukhov similarity theory. While there is some uncertainty in our results due to motion and flow effects, we nevertheless find (except where these effects can be identified) that our results look very similar to those obtained by Miyake *et al.* (1970b), Smith (1967), Busch and Panofsky (1968), McBean (1970), etc., except for the $\overline{wT}$ cospectra. According to similarity theory such normalized spectra and cospectra may be functions of stability (z/L). Since our range of stability is small, we are unlikely to see such effects. However, from results over land with a greater range of stability (Busch and Panofsky, 1968; McBean, 1970), it appears that stability effects for spectra and cospectra are very small for near neutral to moderately unstable ($-z/L$ up to $\frac{1}{2}$ or so) conditions. Thus, it seems that under typical oceanic conditions within a few meters of the surface the velocity spectra, uw cospectra and wq cospectra have "universal" nondimensional forms. Of course any one run (realization) will show some statistical variation. Further, as also noted by Miyake and McBean (1970), the shapes of the *uw* and *wq* cospectra seem to be very similar. The *wT* cospectra do not seem to fit with the theory. This discrepancy may be caused by the fact that similarity theory does not include the effects of longwave radiation on the temperature field which may be quite strong during BOMEX because the absolute humidity is high (Phelps and Pond, 1971).

c. *Momentum flux*

While there is quite a lot of scatter between values in individual runs, the eddy correlation and dissipation techniques agree very well on the average. The values given are for a height of about 8 m rather than the more usual reference height of 10 m but the difference is negligible (typically, C_D would be lowered by about 3%). No trend with wind speed is apparent over our small range of U. Both methods give the same value of C_D of 1.5×10^{-3} with standard deviations of 0.26 for eddy correlation results and 0.40 for the dissipation results. Note that we have not made a stability correction to the wind profile in the production term which would give about 25% larger values for the dissipation method. This additional correction would lead to a rather large C_D of 1.9×10^{-3}. The dissipation method is somewhat empirical, and we feel that the method we have used is the most satisfactory one. It gives good comparisons with the eddy fluxes not only for our results but also for those of Miyake *et al.* (1970a) which do not have uncertainties in them due to flow distortion and motion effects.

The value of the drag coefficient seems a bit large but is not unreasonable, compared to other results both from eddy correlations and profiles. Deacon and Webb (1962) summarize many results, mainly obtained by profile measurements. For 10 m height they give $C_D=(1.0+0.07U)\times10^{-3}$. For our range of wind speed this formula gives values ranging from 1.28×10^{-3} to 1.5×10^{-3}. Hasse (1970) summarizes values of other workers ranging from 1×10^{-3} to 1.8×10^{-3}. From his own results he gives $(1.21\pm0.24)\times10^{-3}$ (mean plus standard deviation) at 10 m height, while Miyake *et al.* (1970a) and Smith (1970) obtain $(1.1\pm0.18)\times10^{-3}$ and $(1.35\pm0.34)\times10^{-3}$, respectively. The Hasse and Miyake *et al.* results were obtained in less unstable conditions than ours. As noted before the convective activity tends to increase $\overline{uw}$ over what it would be in neutral conditions. This effect will therefore cause C_D to increase with $-z/L$, and may at least partially explain the difference from these results. We cannot see any trend in C_D with z/L but our range of z/L is small and C_D's rather uncertain. Hasse suggests that there is such a trend in his results but Smith does not see any systematic stability effects. This possible stability dependence is worth further examination, although the effects may be very difficult to pick out of the natural variability of the process, particularly since the range of stabilities usually encountered at sea is not very large. The value of C_D may also be affected by *Flip*'s interference with the flow which may decrease U from the value typical of the wind field farther away from the ship, although wind tunnel model studies on *Flip* suggest that this effect should be a few percent at most.

d. *Sensible heat flux*

On Fig. 6 we have distinguished between the San Diego and BOMEX data. Like the *wT* cospectrum, the two sets of data seem quite different. The $\overline{wT}$ value for OSU run 3 is omitted since it is based on only 13 min of data. For the San Diego data, where T and q behave in a very similar way, the eddy correlation and dissipation methods seem to agree fairly well and to be related to $U\Delta T$. Hasse (1970) obtains good correlation between $\overline{wT}$ and $U\Delta T$ and gives $C_T=1\times10^{-3}$. Our C_T's for San Diego are consistent with this value. The amount of data is too small to draw any conclusions but the results suggest further comparisons of eddy correlation, dissipation, and aerodynamic methods may be fruitful in temperate regions.

During BOMEX the eddy correlation and dissipation methods do not agree. Nor do they seem to be related to $U\Delta T$. Admittedly the values of ΔT are very small but the errors are unlikely to be large enough to explain the discrepancy. An average error of about 1.5C would be necessary, in contrast to a probable error of 0.3C including thermometer differences and reading errors. Furthermore, ΔT errors cannot explain the discrepancy between the eddy correlation and dissipation methods. The reasons for these discrepancies are rather complicated and depend, at least in part, on the nature of the q and T variations which are quite interesting in themselves. The similarities and differences of the humidity and temperature fluctuations and their relations with the velocity fluctuations are given in Phelps and Pond (1971). [McBean (1970) also compares some of the BOMEX results for T and q with his measurements over land which aids in understanding the BOMEX results for T and q.] In computing ΔT we have not allowed for the fact that the surface temperature will be somewhat lower than the "bucket temperature" which we used since the correction is not well known. We have not included the adiabatic lapse rate either, which would reduce all ΔT's by 0.08C, since the correction is negligible for the San Diego data and immaterial for the BOMEX data. Such corrections would make the BOMEX discrepancies even greater.

For the BOMEX data we must regard only the eddy flux values as reliable (to 10–15%) and accept the fact that the aerodynamic approach is not useful. From a practical point of view there is no real difficulty. The sensible heat flux is a very small part of the total heat flux and does not seem to vary much. We may either take a fixed value of 1.3 mW cm^{-2} or take $H_s=0.1H_L$. Either method should give acceptable results for the early part of the BOMEX experiment.

For the BOMEX data the Bowen ratio R based on the observed eddy fluxes has an average value of 0.10, about what might be expected for this region. Note, however, that because $\overline{wT}$ is not related to $U\Delta T$, formulas for predicting R from ΔT and Δq such as that given by Roll (1965) [$R=0.48\Delta T/(\Delta q)$, made consistent with our humidity units] will not give correct values but values that are too low by a factor of two or more. For the San Diego data the formula agrees fairly well with observed values of R.

e. Latent heat flux

The dissipation method gives values of the moisture flux in good agreement with but a little larger than those from the eddy correlation method on the average. There are uncertainties from the rotation and the assumptions in the dissipation method, but the calibration uncertainties essentially cancel out. The correctness of the dissipation method must be regarded as tentative until further tests are made, but the results are encouraging. The fluxes by both methods show a strong functional relationship with $U\Delta q$. This result needs further testing too over a wider range of wind speed and geographical location. The moisture fluxes range from 125 to 250 cm year^{-1} which seem to be reasonable values.

Based on the eddy correlation measurements we obtain $C_q=(1.23\pm0.17)\times10^{-3}$ while the dissipation method gives $(1.25\pm0.25)\times10^{-3}$. No trend with wind speed or stability is apparent over our fairly narrow range of these parameters. It is difficult to compare this result with other results because they are not based on direct measurements close to the surface. From aircraft observations Bunker (1960) obtains about 1×10^{-3}. Based on 365 days of evaporation pan observations by Wust on the *Meteor* in the Atlantic from 25N to 55S, Sverdrup (1951) obtains values from 1.1×10^{-3} to 1.4×10^{-3} for different geographical regions. The overall average is 1.3×10^{-3}. Phelps (1971) summarizes these and other results including some based on climatological averages which range from 1×10^{-3} to 3×10^{-3}. Deacon and Webb (1962) give values for C_q between about 1×10^{-3} and 1.6×10^{-3} based on their formula for C_D and various hypotheses for the moisture exchange process. Our value is also similar to the value of C_T obtained by Hasse (1970) from a region where (as suggested by the few San Diego results) we might expect C_q and C_T to be about the same.

The derivation of the aerodynamical formulas given in Roll (1965) would suggest $C_q>C_D$ for unstable conditions. For our results $C_q<C_D$ on the average, although, because of the scatter and other uncertainties, the difference may not be significant. A bucket temperature is used rather than the actual surface temperature which would be somewhat lower (e.g., Saunders, 1967). For example, a 1C lower surface temperature would make Δq 20% lower and C_q 20% higher (although the actual difference would probably be smaller). It is, of course, more practical to use a bucket temperature, but then we should not necessarily expect $C_q>C_D$. Furthermore, the relation $C_q\geqslant C_D$ is based on obtaining the bulk formulas by integration of the profile equations; however, because of the peculiar nature of the surface boundary, due to the presence of waves, the profile equations may not be correct very close to the surface. Thus, the bulk aerodynamic approach must be verified and the coefficients obtained by observations rather than theoretical arguments.

On the basis of our present results we suggest that the latent heat flux is given by $1.2\times10^{-3}\ LU\Delta q$ with an uncertainty of about 20%. More direct observations of the latent heat flux are needed to test this result.

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APPENDIX

Supplementary Results

Run	U (m sec^{-1})	$-\overline{uw}$ (cm^2 sec^{-2})	σ_w (cm sec^{-1})	σ_u (cm sec^{-1})	σ_v (cm sec^{-1})	$-\langle R_{uw}\rangle$	$-r_{uw}$	Buoyancy production from $\overline{wT}$ (cm^2 sec^{-3})	Buoyancy production from $\overline{wq}$ (cm^2 sec^{-3})	ϵ (cm^2 sec^{-3})	$\epsilon - B$ (cm^2 sec^{-3})	$\overline{wT}$ (°C cm sec^{-1})	$-\overline{uT}$ (°C cm sec^{-1})	ΔT (°C)	$10^4 N_T$ [(°C)^2 sec^{-1}]	$\overline{wq}$ (cm sec^{-1} μg cm^{-3})	$-\overline{uq}$ (cm sec^{-1} μg cm^{-3})	Δq μg cm^{-3}	$10^4 N_q$ (μg cm^{-3})^2 $\times$sec^{-1}	α
OSU																				
1	5.78	533	29.0	69.1	70.7	0.46	0.266	5.49	1.53	26.5	19.5	1.59	2.73	2.78	1.70	3.22	7.08	4.62	4.66	1.43
2	6.60	724	32.3	75.7	80.0	0.43[a]	0.296	5.49	1.61	36.2	29.1	1.59	3.43	2.78	2.45	3.38	10.1	4.62	5.17	1.31
3	4.78	378	25.8	55.1	60.1	0.49	0.266	3.07	0.74	23.4	19.8	0.89	1.74	2.80	2.45	1.55	0.94	3.87	2.26	1.40
4	6.05	840	38.1	109.0	129.0	0.38[b]	0.203	8.97	2.10	91.8	80.7	2.60	2.70	3 71	2.84	4.41	2.48	5.56	8.56	1.37
5	4.65	356	25.2	58.5	67.1	0.48	0.242	3.00	2.76	31.8	26.0	0.92	1.51	0.63	3.62	5.51	14.7	8.22	25.8	1.52
6	5.55	369	26.4	59.5	72.1	0.49	0.235	3.04	1.99	36.3	31.3	0.93	1.07	0.65	3.56	3.96	14.3	6.48	14.6	1.47
7	7.22	505	32.6	81.5	79.0	0.50	0.190	3.86	3.14	41.6	34.6	1.18	2.43	0.65	3.90	6.25	25.2	6.48	17.1	1.43
8	5.92	618	35.1	79.3	96.5	0.34[c]	0.222	4.25	2.18	67.9	61.5	1.30	3.05	0.70	5.54	4.34	26.0	7.50	34.1	1.34
9	7.21	881	42.1	71.7	100.0	0.44[d]	0.292	4.93	3.74	78.5	69.8	1.51	2.86	0.33	7.48	7.45	18.7	7.79	37.1	1.29
10	6.79	664	29.6	67.3	68.0	0.46	0.333	3.72	2.34	43.5	37.4	1.14	3.03	0.43	4.79	4.65	20.6	6.58	17.7	1.29
11	5.31	383	24.6	56.3	57.1	0.46[e]	0.276	2.90	2.14	26.6	21.6	0.89	2.03	0.35	4.31	4.27	13.8	7.24	17.1	1.46
12	6.51	565	32.8	67.5	63.0	0.47	0.256	3.59	3.18	53.4	46.6	1.10	2.02	1.89[i]	3.50	6.34	19.1	8.04	30.0	1.39
13	5.86	484	30.4	63.4	69.6	0.45[f]	0.251	3.66	3.26	45.5	38.6	1.12	1.66	0.74	5.75	6.51	17.7	8.63	32.2	1.46
14	4.97	352	27.0	61.7	71.4	0.46	0.212	3.59	2.52	34.6	28.5	1.10	0.57	0.66	4.48	5.03	12.1	7.89	20.3	1.59
15	6.78	686	33.8	73.1	74.5	0.45	0.278	3.95	3.98	68.0	60.1	1.21	2.46	0.84	8.55	7.95	28.2	8.99	45.7	1.36
UBC																				
1	6.88	675	33.9	75.3	70.6	0.46[g]	0.264	5.19	3.25	...	...	1.59	...	0.43	...	6.48	...	7.10	...	...
2	6.10	628	30.0	73.1	74.1	0.50	0.274	4.15	3.20	...	...	1.27	...	0.35	...	6.39	...	7.23	...	...
3	5.48	424	26.0	56.0	78.0	0.49	0.291	3.59	2.68	...	...	1.10	...	0.35	...	5.33	...	7.24	...	...
4	5.01	381	22.3	55.1	59.4	0.40[h]	0.310	2.54	1.85	...	...	0.78	...	0.35	...	3.69	...	7.24	...	...
5	3.93	246	22.2	40.1	44.9	0.48	0.276	2.52	2.28	...	...	0.77	...	0.35	...	4.54	...	7.24	...	...

The value of $\langle R_{uw}\rangle$ sometimes appear to be affected by *Flip's* motion. Particularly noticeable values are commented on individually below.

[a] One small value included, probably caused by motion; averaging remaining values gives 0.50.

[b] Low value probably due to motion; note large σ_u/U and σ_v/U, also large C_D even with low $\langle R_{uw}\rangle$ and r_{uw}; cospectral values at very low frequencies give significant contribution to $\overline{uw}$ which is not typical.

[c] Two very low values probably due to motion; note large σ_v indicating large rotation. Average removing two low values is 0.49.

[d] Two lower values, other values slightly over 0.5; note large σ_v.

[e] One low value, neglecting it gives 0.51.

[f] One lower value, neglecting it gives 0.48.

[g] One low value, neglecting it gives 0.51.

[h] One low value, neglecting it gives 0.50.

[i] This value may be 0.89, the recorded values of T_{air} around this run are not very steady. For $\Delta T = 0.89$, $10^3 C_T = 1.9$.

REFERENCES

Bronson, E. D., and L. R. Glosten, 1968: Floating instrument platform. Tech. Rept., Marine Physical Laboratory, San Diego, Calif.

Bunker, A. F., 1960: Heat and water vapor fluxes in air flowing southward over the western North Atlantic Ocean. *J. Meteor.*, **17**, 52–63.

Busch, N. E., and H. A. Panofsky, 1968: Recent spectra of atmospheric turbulence. *Quart. J. Roy. Meteor. Soc.*, **94**, 132–148.

Deacon, E. L., and E. K. Webb, 1962: Interchange of properties between the sea and air: small scale interactions. *The Sea*, New York, Interscience, 43–87.

Grant, H. L., R. W. Stewart and A. Moilliet, 1962: Turbulence spectra from a tidal channel. *J. Fluid Mech.*, **12**, 241–268.

Gurvich, A. S., and S. L. Zubkovsky, 1966: On the estimation of the structure constant of temperature fluctuations in the atmosphere. *Izv. Atmos. Oceanic Phys.*, **2**, 202–204.

Hasse, L., 1970: On the determination of the vertical transports of momentum and heat in the atmospheric boundary layer at sea. Tech. Rept. No. 188, Dept. of Oceanography, Oregon State University, 55 pp. (Translation of a German article of same title, in *Geophysickalische Einzelschriften*, Vol. 11, Hamburg, Verlag, 1968, 70 pp.)

Lumley, J. L., and H. A. Panofsky, 1964: *The Structure of Atmospheric Turbulence*. New York, Interscience, 239 pp.

McBean, G. 1970: The turbulent transfer mechanisms in the atmospheric surface layer. Ph.D. thesis, University of British Columbia.

Miyake, M., M. Donelan, G. McBean, C. Paulson, F. Badgley and E. Leavitt, 1970a: Comparison of turbulent fluxes over water determined by profile and eddy correlation techniques. *Quart. J. Roy. Meteor. Soc.*, **96**, 132–137.

——, R. W. Stewart and R. W. Burling, 1970b: Spectra and cospectra of turbulence over water. *Quart. J. Roy. Meteor. Soc.*, **96**, 138–143.

——, and G. McBean, 1970: On the measurement of vertical humidity transport over land. *Boundary-Layer Meteor.*, **1**, 88–101.

Nasmyth, P., 1970: Oceanic turbulence. Ph.D. thesis, University of British Columbia.

Paquin, J. E., and S. Pond, 1971: The determination of the Kolmogoroff constants for velocity, temperature, and humidity fluctuations from second and third order structure functions. *J. Fluid Mech.* (in press).

Phelps, G. T., 1971: The fluxes of latent and sensible heat in the marine boundary layer. Ph.D. thesis, Oregon State University.

——, and S. Pond, 1971: Spectra of the temperature and humidity fluctuations and of the fluxes of moisture and sensible heat in the marine boundary layer. *J. Atmos. Sci.*, **28**, 918–928.

——, —— and U. Gorner, 1970: Simultaneous measurements of humidity and temperature fluctuations. *J. Atmos. Sci.*, **27**, 343–345.

Pond, S., 1968: Some effects of buoy motion on measurements of wind speed and stress. *J. Geophys. Res.*, **73**, 507–512.

——, S. D. Smith, P. F. Hamblin and R. W. Burling, 1966: Spectra of velocity and temperature fluctuations in the atmospheric boundary layer over the sea. *J. Atmos. Sci.*, **23**, 376–386.

Roll, H. U., 1965: *Physics of the Marine Atmosphere*. New York, Academic Press, 426 pp.

Saunders, P. M., 1967: The temperature at the ocean-air interface. *J. Atmos. Sci.*, **24**, 269–273.

Smith, S. D., 1967: Thrust-anemometer measurements of wind-velocity spectra and of Reynolds stress over a coastal inlet. *J. Marine Res.*, **25**, 239–262.

——, 1970: Thrust-anemometer measurements of wind turbulence, Reynolds stress and drag coefficient over the sea. *J. Geophys. Res.*, **75**, 6758–6770.

Sverdrup, H. U., 1951: Evaporation from the oceans. *Compendium of Meteorology*, Boston, Amer. Meteor. Soc., 1071–1081.

Weiler, H. S., and R. W. Burling, 1967: Direct measurements of stress and spectra of turbulence in the boundary layer over the sea. *J. Atmos. Sci.*, **24**, 653–664.

Wyngaard, J. C., and O. R. Coté, 1971: The budgets of turbulent kinetic energy and temperature variance in the atmospheric surface layer. *J. Atmos. Sci.*, **28**, 190–201.